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Final Report

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CANADA-SASKATCHEWAN CONSERVATION AND RENEWABLE ENERGY DEMONSTRATION AGREEMENT

On March 18, 1980, the governments of Canada and Saskatchewan entered into a Conservation and Renewable Energy Demonstration Agreement. The Agreement, which terminates March 31, 1984, funds the development and demonstration of a wide range of conservation and renewable energy technologies. The program is funded on an equal cost-shared basis by Canada and Saskatchewan, and is administered by Saskatchewan.

The objectives of CREDA are:

- To develop and demonstrate promising new technologies which exploit renewable energy resources, conserve energy, or make its use more efficient;
- To create employment in new or existing industries;
- To develop broad public awareness of the potential of renewable energy and energy conservation technologies.

This report outlines the results of a project funded by the Government of Saskatchewan as represented by Saskatchewan Energy and Mines, and the Government of Canada as represented by Energy, Mines and Resources Canada, under the terms of the Renewables-Conservation Demonstration Program, and contracted with the party identified herein.

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Flax Straw Burner

SASK 13

Final Technical Report
on a Renewables-Conservation Demonstration Program Project

Conducted By

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And Supported By

Saskatchewan Energy and Mines
and
Energy Mines and Resources Canada

Project Leader: W.A. Keith

Miscellaneous
Report FP-28

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1.1 The Nature of the Problem

There are currently some 50,000 rural residential customers using fuel oil for space heating in Saskatchewan. Space heating with oil is currently more expensive than heating with electricity or natural gas. Because of the history of escalating oil costs, together with concerns about the security of oil supply, many farmers are looking at other heating options for meeting their space heating needs.

1.2 Background

Farmers grow a number of crops from which the waste or residual materials (straw, chaff) can be used as a renewable energy resource. Flax straw is an example of a waste material that cannot easily be recycled into the soil as a fertilizer or used as a cattle feed. Normally, flax straw is burned in the field and the residue is plowed into the soil. The use of flax straw as a source of energy for grain drying and for large heating applications has been investigated by researchers (1). Conversion efficiencies as high as 70% have been measured. Moreover, commercial equipment is currently available to meet these applications.

Interest has focussed on flax straw as a renewable energy source for two reasons: firstly, it is not particularly suited to other applications; secondly, it has a fairly high calorific value. As a generally accepted rule of thumb, a bale of flax straw has about the same heating capability as a US gallon of fuel oil, given typical conversion efficiencies for combustion of the two fuel types. Actually, the calorific value of a bale is 75% higher than that of a US gallon, but allowing for respective conversion efficiencies of 35% and 60% the heating output of a bale of flax straw is very nearly the same as that of a US gallon of oil.

The initiative for this particular project came from Mr. Keith, a farmer living near Sovereign, Saskatchewan. Mr. Keith had already built a prototype flax-straw heating system and had used it to heat a workshop by radiation and natural convection. He wished to explore the possibilities of developing this design to heat both the farm house and the workshop. He made a submission to Saskatchewan Energy and Mines, who were administering the Federal-Provincial Conservation and Renewable Energy Demonstration Agreement (CREDA). This submission was reviewed and approved under the CREDA program. Saskatchewan Research Council was engaged by Saskatchewan Energy and Mines to assist Mr. Keith in the technical aspects of the design, construction and operation of the system. Also, SRC was required to monitor and evaluate the system.

This report presents the details and findings of the project.

The objectives of the project were:

- to design and build a centrally-located flax-straw heating system on a farm,
- to demonstrate the system to other farmers and interested people,
- to evaluate the ability of the system to heat a farm house and a large workshop,
- to monitor the energy consumption and detailed performance of the system,
- to assess the practicality of this type of system for general application on farms in Saskatchewan.

This report is concerned with the technical and economic aspects only, and does not cover the demonstrational program that was built into this project.

3.1 General

The workshop was heated originally with a combustion unit built by Mr. Keith from two steel drums, capable of burning both wood and flax straw. A photograph of the unit is given in Appendix A.

The intention was to build a new central heating unit that would supply heat to both the farm house and the workshop. The most practical approach was to use hot water as the heating medium. This would allow the use of thermal storage to deliver heat when the furnace was inactive. The detailed specifications of the system, as prepared by Mr. Keith, are given in Appendix B.

The general site layout is shown in figure 1. It was felt that there might be some small risk of fire or explosion with the prototype heating system, and it was therefore decided to house the combustion unit in its own building, as shown in figure 1.

3.2 House Details

The farm house was built before 1975 and consisted of a bungalow with full concrete basement. The livable floor area was 140 m^2 (1500 ft^2). The existing furnace was a forced-air, oil-fired unit.

The ceilings were insulated to an estimated level of RSI 5.6 and the walls to RSI 2.1. The basement had been partly developed, with bedrooms, and these were insulated to RSI 2.1 against the foundation wall.

3.3 Details of the Workshop

The workshop was a quonset unit insulated to RSI 3.5. The floor area was 280 m^2 (3000 ft^2). The quonset construction included pony walls; it was insulated and finished with an airtight vapour barrier and gypsum board. The machinery entrance door was insulated and fitted with special seals to reduce air leakage heat losses.

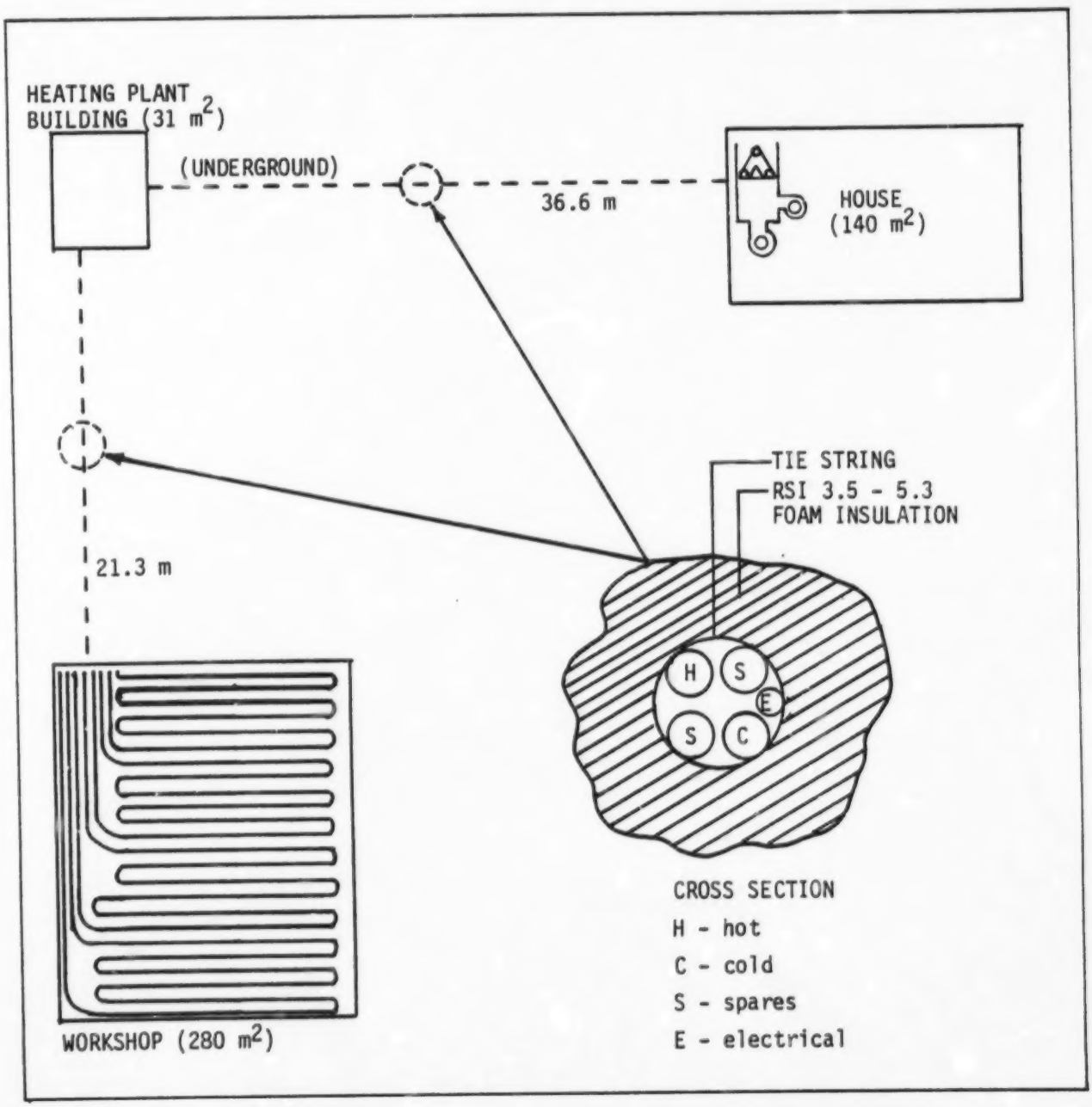


Figure 1. Site Layout and Piping Schematic

3.4 The Heating Plant Building

This was constructed specially for the project, to house the flax straw burner. It had a floor area of 31 m^2 (336 ft^2) and was insulated to RSI 3.5 in the walls and ceiling. A section of the building was used for storage of the flax straw.

3.5 The Flax Straw Burner

The burner was designed by Mr. Keith with assistance from SRC. It was designed to accept a maximum of three standard flax straw bales (approximate dimensions 360 mm x 460 mm x 910 mm). The design was developed with an eye to making the best use of available salvage material and off-the-shelf components.

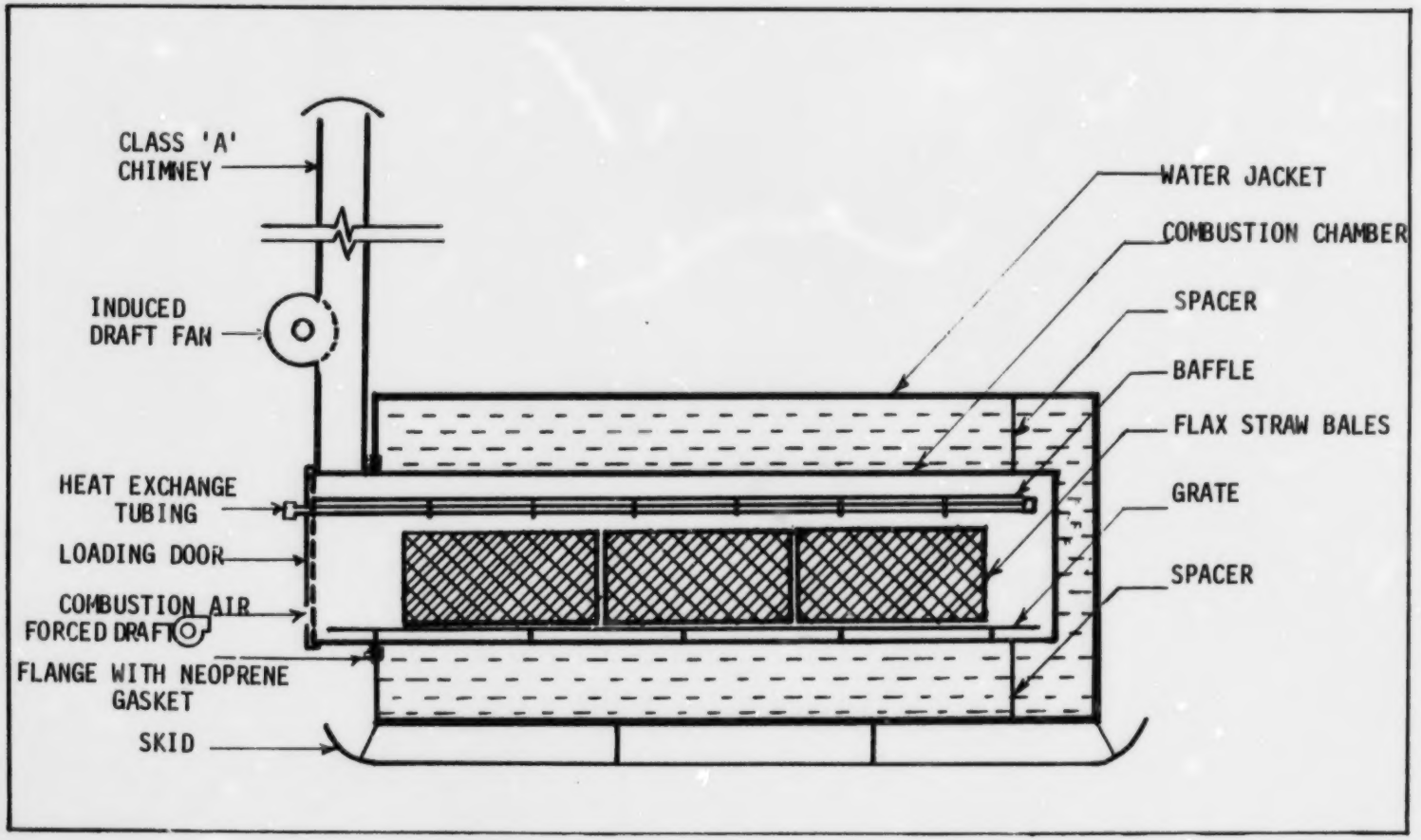
The design of the burner is shown schematically in figure 2. Detailed specifications are given in Appendix B and photographs of the unit are given in Appendix A.

The combustion chamber (or firebox) was constructed from steel pipe of diameter 660 mm (26"). This was attached to the water jacket with a bolted flange and neoprene gasket (figure 2). Note that the back end of the combustion chamber was free to move inside a supporting spacer. This design avoided weld failure due to thermal expansion.

Draft air was supplied through the loading door and was distributed along the combustion chamber through an inverted steel channel beam fitted along the bottom and drilled with a series of air holes. This detail can be seen in one of the photographs in Appendix A.

To increase the heat transfer to the water a steel heating coil was fitted near the top of the chamber. This utilized a 30 m (100 ft) length of 25 mm (1") steel pipe. A baffle plate was fitted over the top of this heating coil. The purpose was to extract

Figure 2. Schematic of Flax Straw Burner



more heat from the combustion gases by diverting them to the back of the combustion chamber, over the top of the baffle and up the chimney.

The unit was provided with an air supply fan and an induced draft fan , which were used only when starting up the burner.

The inside of the water jacket and the outside of the combustion chamber were painted with marine-quality epoxy paint to prevent these surfaces from rusting.

3.6 The Hot Water Circuit

The water jacket served both as a heat collector from the combustion gases and as a thermal storage tank. It consisted of a modified boiler and had a capacity of 4550 L (1000 Imp. Gallons). It was provided with various hydronic circuits and controls as shown schematically in figure 3.

The heat-collecting efficiency of the water jacket was improved by drawing water from the bottom of the jacket, then pumping it through the heat exchanger and back into the jacket - at the top (figure 3).

The water jacket was provided with an expansion tank, a pressure-relief valve, a thermometer and a pressure gauge. The expansion tank consisted of a 205 L (45 Imp. gallon) drum.

Individual hot-water heating circuits were run to the house and the workshop. Each was provided with a pump, controlled by thermostats in the house and workshop. The circuits were provided with an automatic air vent to remove trapped air from the water system.

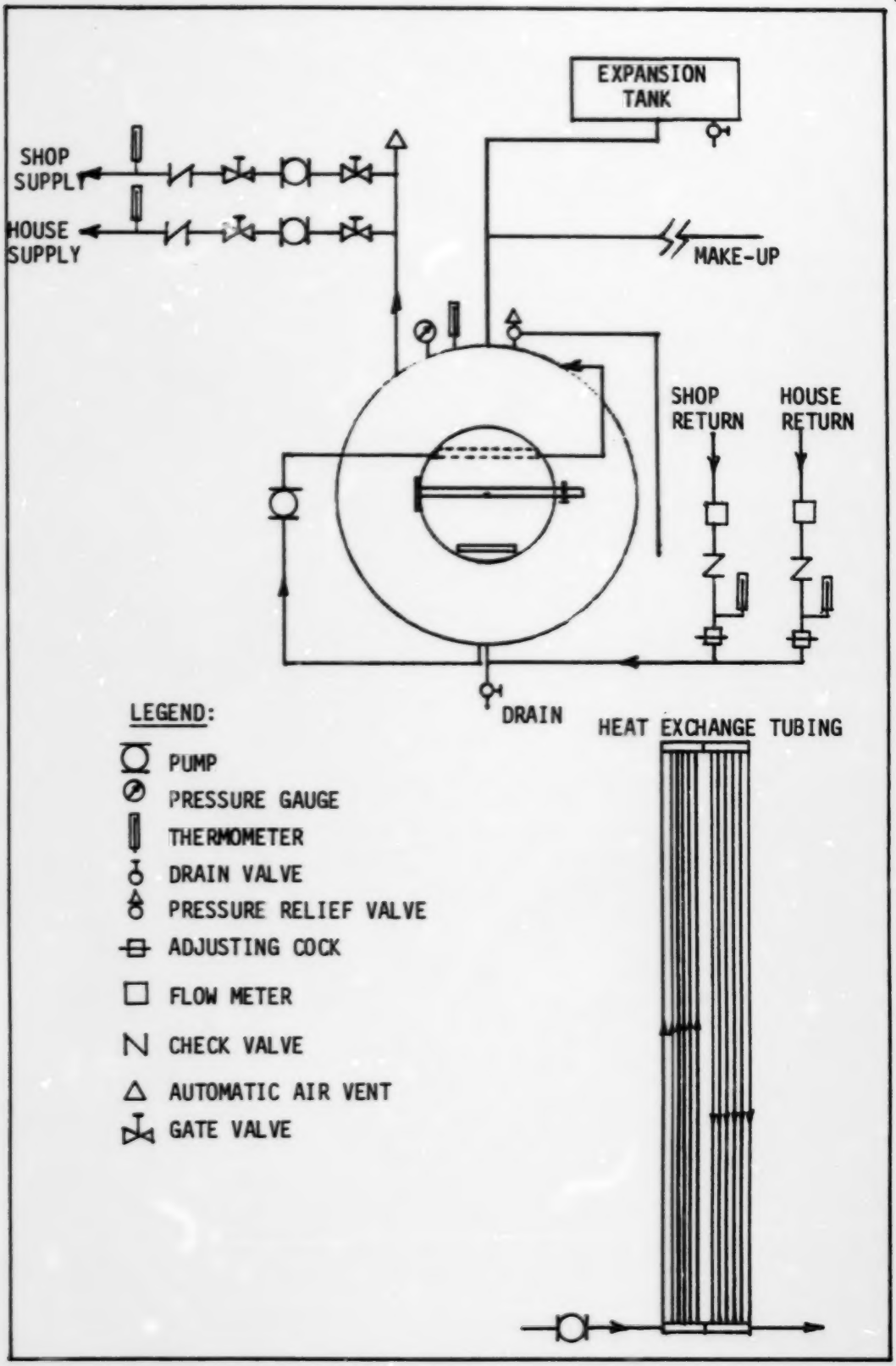


Figure 3. Piping and Control Schematic

The hot water circuits from the heating plant to the house and workshop were made of 25.4 mm (1") black polyethylene pipe. Because of the upper temperature limitations of this material, the water system was designed to run at a maximum temperature of 66°C (150°F). The supply and return pipes and the necessary electrical and monitoring cables were strapped together. The bound assembly was buried at a depth of 1.2 mm (4 ft) below grade and was insulated with foamed-in-place urethane (see photographs in Appendix A). The insulation level was estimated to range from RSI 3.5 to RSI 5.3. Figure 1 shows details of the assembly. It should be noted that the type of urethane used in this installation was suitable for below-grade application. However, some specialists have doubts about the integrity of the material over the long term.

The existing furnace in the house was modified to accept a hot-water heating system. This consisted of an A-coil mounted in the warm-air supply plenum of the furnace (see photograph in Appendix A). The oil combustion unit was retained as a back-up heating system, and the furnace fan was set to run continuously.

The workshop was provided with a floor heating system. This consisted of a total of 366 m (1200 ft) of 25.4 mm (1") diameter black polyethylene pipe embedded in the concrete floor slab. The pipe was divided into four separate circuits or zones, each with its own individual control valve system. The objective was to provide good zonal heating control and shut-off of redundant circuits in the event of long-term pipe failure.

4.1 General approach

The object of the monitoring was to evaluate the effectiveness of the flax-straw burner in the proposed mode of operation, and to determine the useful heat output of the burner in this typical mode of operation. There were three ways of accomplishing this:

- by measuring the temperature rise in the boiler for a known fuel input,
- by performing a detailed flue gas analysis,
- by measuring the heat input and heat output of the system over time.

The last approach was selected because it is a straightforward and well-accepted method of determining the efficiency of a heating system. Moreover, it provides information on system temperatures and flowrates, and on the long-term reliability of the system.

With this approach, the monitoring must concentrate on three areas of performance:

- The indoor temperatures of the house and workshop, together with the ambient exterior temperature. These can be analysed to give details of the varying heating loads imposed on the system.
- The actual heat delivered from the system to the house and workshop. This involves continuous monitoring of water flowrates and the temperatures at various points in the water circuit.
- The temperature history of the water jacket, to determine its heat storage capabilities and its ability to heat the house at night without the need for re-stoking.

4.2 Instrumentation Details

The layout of the monitoring system is shown schematically in figure 4. The thermocouple points are summarised in Table 1 and the monitoring equipment is summarised in Table 2.

A total of 28 thermocouples was installed, but only 13 of these were relevant to the final analysis. Temperature readings were sampled automatically at 15-minute intervals on the Fluke Data Logger, located in the heating plant building.

The on-off cycles of the water pumps were recorded on a Rustrak recorder, and the cumulative flowrates were recorded on the Neptune water meters. The recorder and water meters were located inside the heating plant building.

Inside the house, a Rustrak recorder was installed to record the on-off cycles of the furnace blower and the fuel-oil pump.

A floor-scale, with legal trading accuracy, was installed in the heating plant building to weigh the bales before these were loaded into the burner. Records of the loaded weights were kept in a daily log.

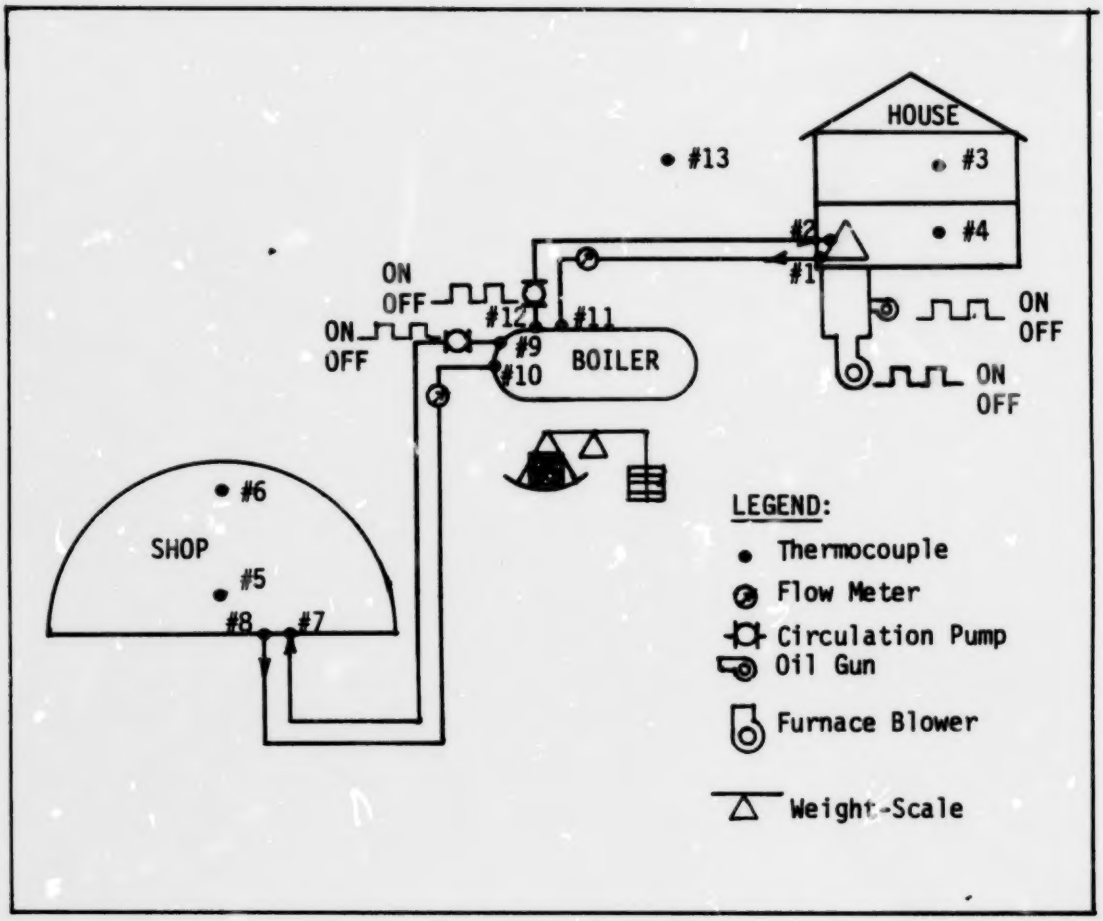


Figure 4. Instrumentation Layout

Table 1. List of Thermocouple Locations

Thermocouple #	Location
1	Inlet water temperature to 'A' coil in the house
2	Outlet water temperature from 'A' coil in the house
3	House interior air temperature on upper level
4	House interior air temperature on lower level
5	Shop interior air temperature (4' above slab)
6	Shop interior air temperature (ceiling level)
7	Inlet water temperature to the shop concrete slab
8	Outlet water temperature from the shop concrete slab
9	Storage tank supply water temperature to shop
10	Storage tank return water temperature from shop
11	Storage tank supply water temperature to house
12	Storage tank return water temperature from house
13	Outdoor air temperature

Table 2: List of Instrumentation

Instrumentation	Measurement	Remarks
1 Fluke 2200 Data Logger	thermocouple recorder	.1°C resolution
13 Type 'T' thermocouple	temperature at various locations	±.5°C accuracy
2 Rustrak 4 Channel event recorders	pumps and blower on/off status	
2 Neptune hot water meters	water flow volume	utility billing accuracy
1 Scale	weight of straw	legal trading accuracy

5.1 The Monitoring Period

The schedule of the project called for monitoring from mid-January to mid-March, 1982. The fabrication and installation were delayed by the late arrival of some components and it was not possible to commence monitoring until early March. Commissioning tests were conducted on the heating system, using the oil furnace as a heating back-up when necessary. These tests were completed by March 8, 1982.

The heating system was monitored from March 8 to April 21, 1982 - a period of about 6 weeks. In this period there were a number of power line voltage fluctuations - not uncommon in rural areas. These interrupted the operation of the Fluke data logging system and severely reduced the period over which useful data were obtained.*

As a result, there was only one seven-day period in which the data were reliable enough, and complete enough, to permit a detailed analysis of system performance. Even this period was subject to operational problems: by mistake, the farmer had disconnected the recording instrument on the oil furnace.

5.2 Operation of the Burner

The following procedures were developed for starting up the burner:

- Straw bales were loaded into the combustion chamber and the fire was started with the assistance of newspaper. If the bales were slightly wet, fuel oil was used to start the fire.
- During start-up the air supply fan and the chimney draft fan were activated.
- When starting up with a cold system, the water circuits to the house and workshop were closed off to allow the temperature to build up more rapidly in the water jacket.

* This is evident in the untreated experimental data, which are presented in Appendix D.

The heating system was designed for manual bale-loading and manual control. Bales were loaded intermittently and controls were adjusted from time to time by the farmer. As a result, the heating system never operated in a steady state for any length of time. This had an influence on the selected method of analysis. It meant that the analysis of performance would have to based on a time scale of about a week, to eliminate the transient effects of the various changes in the system.

5.3 Flax Straw Consumption

The bales were weighed and the consumption was recorded in a log book throughout the monitoring period. These results, together with outdoor temperature data, are presented in figure 5 and Table 3. A total of 435 bales was consumed in the 45-day monitoring period. This amounted to an average of between 9 and 10 bales per day. Note that the average weight of a bale was about 16.8 kg (37 lb).

No conclusive correlation appears to exist between the mass of straw consumed and the mean daily temperature (figure 5). This can be attributed to the large amount of thermal storage in the system, and to the fact that the bales were loaded partly when needed and partly at the convenience of the farmer. If the loading happened to be light on a particular day, then the system would be able to maintain an adequate delivery of heat from thermal storage for some considerable time.

Although there is no detailed correlation between outdoor temperature and straw consumption, there is an obvious general trend from April 3 to April 21. In this period the general increase in outdoor temperature is matched by a general decrease in the rate of consumption (figure 5). In theory, because of the large thermal storage capacity of the water jacket, the fuelling rate should lag behind the outdoor temperature variations. This is not evident when one looks at the detailed variations, and this emphasises the need to employ relatively long time scales when analysing the performance of the system.

Table 3. Outdoor Temperature and Flax Straw Input

Date	Mean Outdoor Temperature (°C)	Mass of Flax Straw Input (kg)	Date	Mean Outdoor Temperature (°C)	Mass of Flax Straw Input (kg)
March/82			April/82		
8	-22.5	35.9	1	-7.3	340.1
9	-11.3	143.2	2	-13.5	263.0
10	-6.5	174.6	3	-16.0	104.3
11	-6.3	128.6	4	-13.0	249.9
12	-6.3	265.0	5	-15.5	267.6
13	-10.8	198.6	6	-8.5	212.7
14	-9.0	57.7	7	-7.5	160.5
15	-1.8	193.6	8	-5.3	170.0
16	-2.5	184.1	9	-4.8	106.4
17	-8.5	252.3	10	-5.0	160.0
18	-9.0	258.6	11	0.8	108.6
19	-3.3	123.6	12	-0.3	196.4
20	-11.0	197.7	13	6.8	90.0
21	-3.3	195.9	14	6.8	66.4
22	-4.5	213.2	15	2.8	175.0
23	-1.5	314.6	16	3.8	105.9
24	-5.0	142.7	17	6.5	0.0
25	-9.5	216.5	18	4.0	50.0
26	-7.0	229.1	19	2.0	52.7
27	-2.0	176.4	20	4.8	0.0
28	-4.3	144.6	21	8.8	50.0
29	1.3	156.4			
30	-4.5	206.4			
31	-11.5	170.5			

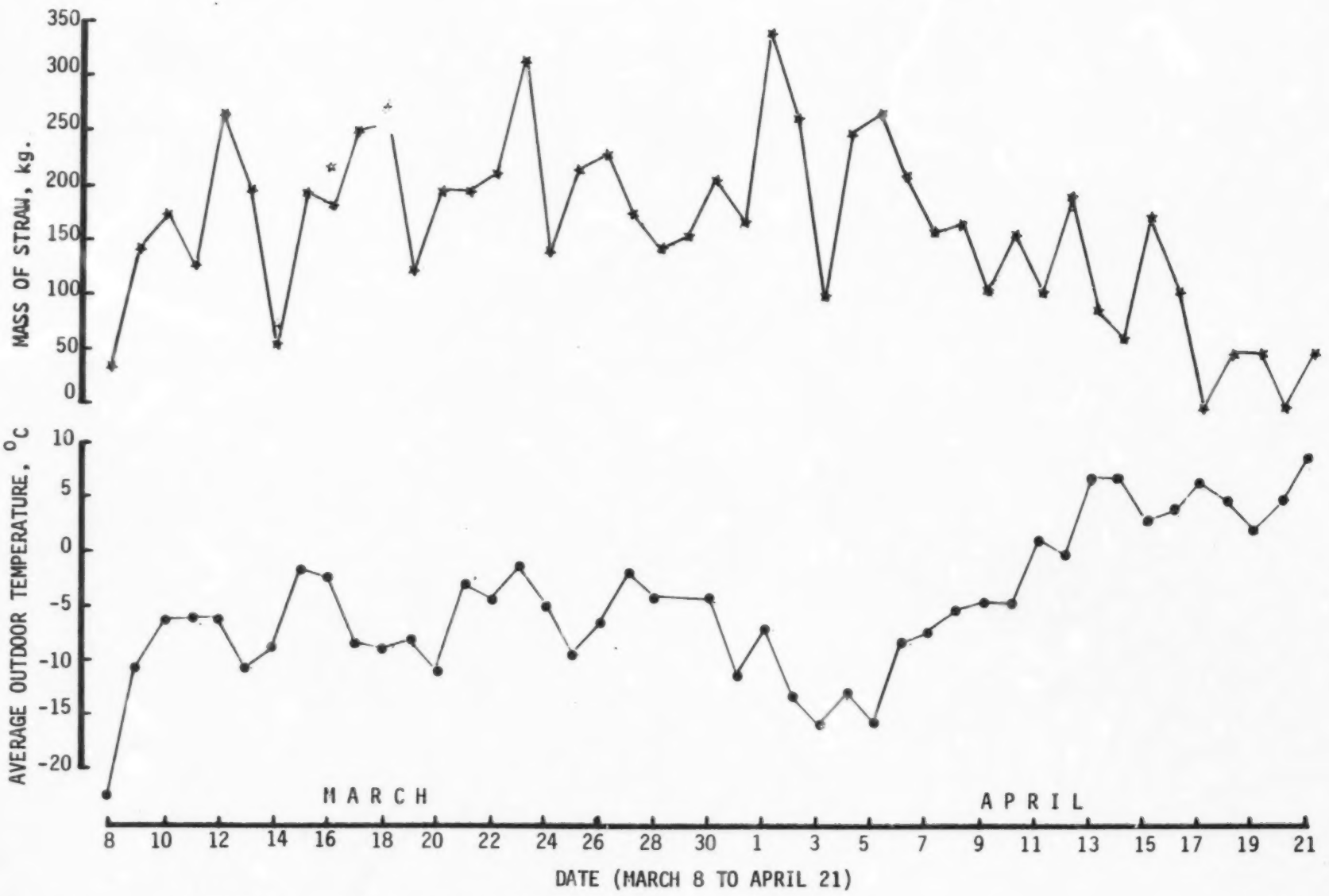


Figure 5. Bale Input and Outdoor Temperature History

5.4 Heating System Output

The most comprehensive set of field data were obtained in the period April 1 to April 7. The detailed analysis of the system performance is therefore confined to this 7-day period. The relevant data for the house are summarised in Table 4 and for the workshop in Table 5. The water temperature difference given in these tables represents the mean daily temperature drop in the water as it flows through either the house heating system or the workshop heating system. Knowing this figure, and the water flow rates, the heat delivered by the water can be calculated relatively easily. This is done later in the report. Figure 6 summarises the main variations over the seven-day period.

5.5 Operational Aspects

There were no detectable leakage problems or line-freezing problems. The heating system was pressurized and tested before the water system was filled. It was able to maintain pressure for some time without apparent leakage. The system was then filled with a mixture of 90% water and 10% glycol, and again there was no sign of leakage. No leakage problems were encountered during the monitoring period, though it should be pointed out that this would be unlikely anyway since the system operates at a relatively low pressure.

Neither the water lines nor the burner unit have displayed any signs of freezing during the course of the project. At an early stage of the design there was some thought of using a 50%-water, 50%-glycol mixture for the water system, which would have given protection down to temperatures of -37°C. However, because the underground lines were well buried and insulated, and because of the high cost of glycol for such a large system, it was decided to use a 10% glycol mixture.

This weak glycol mixture appears to have worked satisfactorily in this instance, though this may not always be so. With this concentration there still remains a distinct risk of freezing that is difficult to quantify. The water jacket and the exposed pipes in the heating plant building will certainly freeze if left

Table 4. House Monitoring Results (1982)

Date	Total Pump On-Time (h)	Water Flowrate (kg/s)	Average Water Temperature Difference (°C)	Rate of Heat Supplied (kW)	Energy Supplied (GJ)
April					
1	17.45	0.40	4.29	7.13	448.3
2	14.45	0.40	5.44	9.05	471.3
3	11.80	0.40	4.02	6.69	284.5
4	4.85	0.40	5.11	8.50	148.6
5	10.70	0.40	3.72	6.18	238.3
6	13.60	0.40	3.53	5.88	287.9
7	7.55	0.40	5.07	8.43	229.2

Table 5. Workshop Monitoring Results (1982)

Date	Total Pump On-Time (h)	Water Flowrate (kg/s)	Average Water Temperature Difference (°C)	Rate of Heat Supplied (kW)	Energy Supplied (GJ)
April					
1	9.15	0.30	11.84	14.95	492.6
2	9.25	0.30	15.13	19.09	636.2
3	2.30	0.30	11.09	13.99	116.9
4	14.70	0.30	12.79	16.14	854.6
5	23.00	0.30	9.76	12.31	1020.2
6	20.85	0.30	6.63	8.36	628.0
7	5.00	0.30	10.64	13.43	241.9

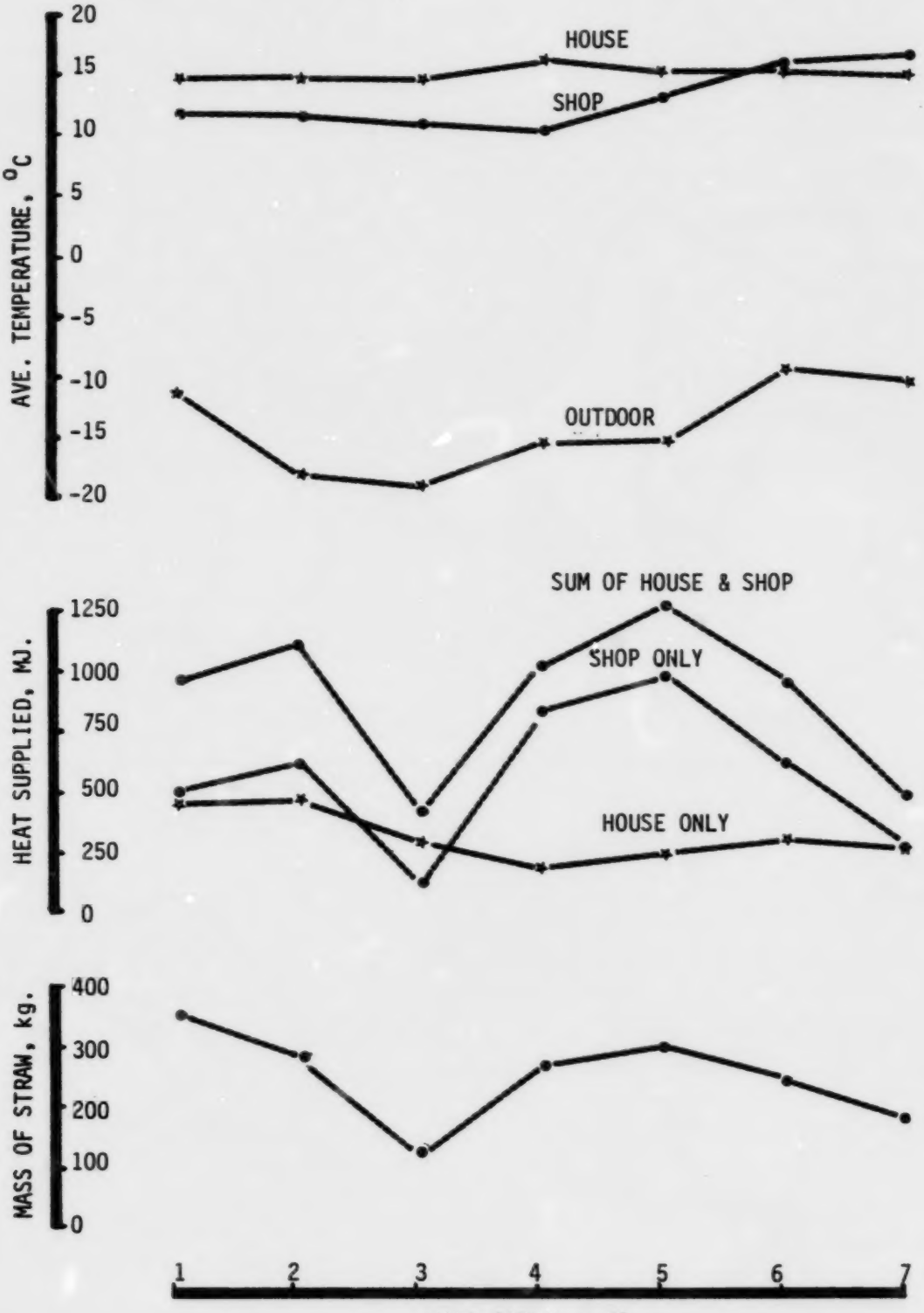


Figure 6. Heating System Performance Per Day

unattended for any length of time in winter. The underground pipe runs will also freeze if the contained water/glycol temperature falls below -5°C. The likelihood of this happening is dependent on many factors, including the climate, the depth of burial, the level of pipe insulation, the duration of the no-flow situation and the previous history of the system operation - which affects the size of the warm-soil region that is built up around the pipes.

The risk of freezing in the heating plant building can be avoided by using a portable back-up heater (propane or electric). The same applies to the workshop. In the house the existing oil furnace provides adequate back-up and this can also be used in an emergency to protect the water lines. This can be done by circulating water continuously through the house circuit. The water picks up heat from the furnace as it passes through the A-coil, and this will prevent the water lines from freezing. This mode of operation has not been tested, though it seems eminently reasonable.

6.1 Analytical theory

Heat input:

The heat input of the flax straw is equal to the product of the mass of the straw and the calorific value of the straw. This leads to the following equation:

$$q_i = \frac{M.C}{t_f} \qquad 1.$$

where: q_i = heat input rate (kW)

t_f = time over which the straw is used (s)

M = mass of straw used in time t_f (kg)

C = calorific value of straw (kJ/kg)

Heat output:

When heated water passes through the house or the workshop it gives up a certain amount of its heat to these buildings. At any instant, this heat output of the water is given by:

$$q_o = \dot{m}.C_p.\Delta T \qquad 2.$$

where: q_o = heat output rate of water (kW)

$\dot{m}$ = water flowrate (kg/s)

C_p = specific heat of water (kJ/kg/°C)

ΔT = Temperature difference between water flowing into the building and water flowing out (°C)

To obtain the total amount of heat delivered by the water over a selected period, equation 2 must be integrated as follows:

$$E = \dot{m}.C_p.\int_{t=0}^{t=t_p} \Delta T.dt \qquad 3.$$

where: E = energy output per day (GJ)

t_p = the on-time of the circulating pump per day (s)

In practice, the temperatures were sampled at intervals of 15 minutes. Equation 3 can therefore be written as follows:

$$E = 15 \times 60 \times \dot{m}.C_p.\sum_{n=1}^{m} \Delta T \qquad 4$$

where: m = number of 15-minute intervals in the day

The average daily water temperature difference can be calculated from:

$$\overline{\Delta T} = \frac{1}{m}.\sum \Delta T \qquad 5$$

Hence, equation 4 can be re-written:

$$E = \dot{m}.C_p.\overline{\Delta T}.m\Delta t \qquad 6.$$

where: $m\Delta t$ = pump on-time in the day.(s)

System Efficiency:

This is defined as the combined heat output to the house and workshop, divided by the total calorific value of flax straw loaded into the burner. The average efficiency over D days is as follows:

$$N = \frac{\sum_{n=1}^{D} (E_h + E_w)}{\sum_{n=1}^{D} q_i . 86400} \qquad 7.$$

where: N = overall system efficiency

E_h = energy supplied to house per day (GJ)

E_w = energy supplied to workshop per day (GJ)

86400 = number of seconds in a day

D = number of days in analytical period.

6.2 Overall Efficiency

This was calculated using the analytical equations developed above. The analysis was confined to the seven-day period from April 1 to April 7. This was the only extended period in which the field data were not disrupted by operational problems, and the period was considered to be long enough to overcome any short-term transient effects.

To allow the calculation of heat input according to equation 1, it was necessary to know the calorific value of the flax straw. A proximate analysis was conducted by the Analytical Services Section of SRC, and the results of this analysis are presented in Appendix C. The measured calorific value was 15.24 MJ/kg. The total mass of flax straw burned in the seven-day period was 1599 kg, giving a total heat input of 24.37 GJ.

The heat output was calculated from equation 6. The base data for this equation have already been given in Table 4 and 5, for the house and the workshop. The final two columns in these tables give the heat supplied to the house, as calculated from equation 6. The main data pertaining to heat input and output are presented in Table 6.

Table 7 presents the heat output in the form of heat supplied per heating degree-day. This information will be used in a later stage of the analysis.

Using the data from Table 6, together with the results of the proximate analysis, the overall efficiency of the system can be calculated by using equation 7. The main factors and results in this calculation are summarised in Table 8. The estimated overall efficiency of the flax straw heating system is 25%.

Referring to Table 6, it will be noted that the outdoor temperatures ranged from -7.3°C to -15.5°C over the analysed period. These temperatures were sufficiently low to give a fairly good test of the

Table 6. Analysis of Heating Performance, April 1 to 7/82

			House				Workshop			
Date	Outdoor Temperature (^{o}C)	Fuel Input (kg)	Indoor Temperature (^{o}C)	DD*	Rate of Heat Supplied (kW)	Energy Supplied (MJ)	Indoor Temperature (^{o}C)	DD*	Rate of Heat Supplied (kW)	Energy Supplied (MJ)
1	-7.3	340	19	26.3	5.2	448	16	23.3	5.7	493
2	-13.5	263	19	32.5	5.5	471	16	29.5	7.4	636
3	-16.0	104	19	35.0	3.3	285	15	31.0	1.3	116
4	-13.0	250	20	33.0	1.7	149	15	28.0	9.9	855
5	-15.5	268	20	35.5	2.8	238	17	32.5	11.8	1020
6	-8.5	213	20	28.5	3.3	288	20	28.5	7.3	628
7	-7.5	161	19	26.5	2.7	229	21	28.5	2.8	242
Total (average)	(-11.6)	1599		217.3	(3.5)	2108		201.3	(6.6)	3990

* degree days (^{o}C)

Table 7. Summary of Space Heating Output, April 1 to 7/82

Summary of Heating Performance	House	Workshop
Average Rate of Heat Supplied	0.113 kW/DD	0.230 kW /DD
Average Energy Supplied	9.7 MJ/DD	19.8 MJ/DD

Table 8. Calculation of Overall Efficiency, April 1 to 7, 1982

Performance Parameter	Evaluation	Comments
Heating value of fuel	15.24 MJ/kg	see Appendix C
mass input	1599 kg	from Table 6
heat input	24,369 MJ	
heat output		
- house	2108 MJ	from Table 6
- workshop	3990 MJ	
- total	6098 MJ	
Overall efficiency	25%	(100x6098/24,369)

heating capabilities of the flax straw burner. Note also that a fairly uniform house temperature was maintained in this period. However, the workshop temperature was controlled by the farmer to accommodate his work schedule. From April 1 to 3 the shop temperature was maintained at a comfortable working temperature of 15°C. After this time the owner was planning to run a demonstrational seminar in the workshop and he therefore increased the workshop temperature to about 20°C over a two-day period (April 3 to 5). This was achieved by increasing the rate of heat delivery to the workshop by stoking the burner and activating more of the four heating circuits in the quonset. The boiler had to be stoked 24 hours before the seminar to produce an adequate rise in temperature in the large thermal storage water jacket.

It should also be noted that the oil furnace was used in the house for a short interval during the analysed seven-day period. The amount of heat delivered by this operation cannot be estimated accurately, since the Rustrak on-off recorder had been disconnected (see remarks earlier). The operation of the oil furnace can be inferred from the monitored temperatures in the furnace return-air plenum and supply plenum. However, these monitored temperatures were sampled at 15-minute intervals, which does not allow an accurate assessment of the unrecorded furnace use.

The unrecorded furnace use and the seminar that was held in the workshop must have had a significant effect on the operation of the heating system. They do not introduce any serious errors into the 25% estimated efficiency (above), but they affect the analysis in the following pages.

6.3 Annual Performance of the System

This involves four main considerations:

- The design heating load imposed on the system by the house and workshop combined.
- The annual space heating requirements of these two buildings.

- The rated input and output of the flax straw burner.

- The annual flax straw requirements.

The estimated values of these various factors are presented in Table 9, which is based on the following analytical stages.

The 2½% design outdoor temperature for the Rosetown area (near Sovereign) is -33.3°C. The mean indoor temperature of the house was taken to be 20°C, and that of the workshop was taken to be 16°C. This gives the design temperature differences shown in Table 9. Taking 30-year average climatic data for Rosetown, and allowing for the lower operating temperature of the workshop, we have a heating degree-day figure of 5972 for the house and 5268 for the workshop.

The second section in Table 9 concerns the space heating load of the house and workshop, expressed in kilowatts.This has been determined by two methods:

- The first method is termed 'experimental' and is based on the results presented in Table 7. Thus, for the house, the design heating load is equal to the design temperature difference (53.3°C) multiplied by the derived rate of heat supplied (0.113 kW/DD). This gives a figure of 6.02 kW/day. The design heating load of the workshop was derived by a similar calculation.

- The details of the house construction were used as input for the computer program HOTCAN. This program estimates the space heating performance of houses using constructional details and local climatic records (2). The input data used for HOTCAN are given in Appendix E, which includes data for both the house and the workshop.

The third section in Table 9 concerns the annual space heating requirements of the buildings. In the column labelled 'experimental', the figures represent the product of annual heating degree-days (first section of Table 9) and average energy supplied (from Table 7). Thus, for the house, the result is 9.7 x 5972 = 57.9 GJ. The HOTCAN results are obtained by the same

process and using the same set of input data as described above.

The difference between the workshop 'experimental' data and HOTCAN data is fairly small: 8.8% for the heating load and 15.7% for the annual space heating requirements. This is certainly within the expected accuracy of the experimental method. But for the house, the HOTCAN predicts values that are about 2.4 times higher than the experimental values. The HOTCAN data are believed to be the more accurate of the two, since the experimental data are subject to uncertainties in the use of the oil furnace (see section 6.2, page 28). Furthermore, the HOTCAN predictions are more in line with the established space heating requirements of houses of this age, style and size (3).

The next section in Table 9 concerns the flax straw burner performance. The rated output capacity is 48 kW, based on the measured 25% efficiency. This is approximately 40% higher than the design heating load of 29.0 kW appearing in section 2 of Table 9. For the HOTCAN design conditions the required burn rate is 1.63 bales per hour, while the achievable maximum burn rate is 2.68 bales per hour. Taking the HOTCAN data as a pessimistic case, it is clear that the burner is capable of meeting the heating demands of the house and workshop combined.

To meet the annual space heating requirements of 228.5 GJ, as predicted by HOTCAN, a total 59,970 kg of flax straw will have to be burnt each year - equivalent to 3,570 bales. This can be produced by harvesting about 132 acres of flax straw, given a yield of 453 kg (1000 lb) per acre.

6.4 Heating System Losses

The losses from the heating system can be divided into two main components:

- losses from the underground piping between the buildings,
- losses from the water jacket of the burner unit.

Table 9. Annual Heating System Performance

Performance Parameter	Evaluation		Comment
Degree Days (^{o}C)	House	Workshop	Rosetown, Sask.
- design (2½%)	53.3	49.3	
- annual	5972	5268	
Design Heating Load	Experiment	HOTCAN	- experiment: see Table 7
- house (kW)	6.0	16.7	
- workshop (kW)	11.3	12.3	- HOTCAN: a computer program for building heating analysis
- total (kW)	17.3	29.0	
Annual Space Heating Requirements			
- house (GJ)	57.9	140.6	see above note
- workshop (GJ)	104.3	87.9	
- total (GJ)	162.2	228.5	
Flax-Straw Burner Performance			
- efficiency		25%	see Table 8
- maximum bale capacity		3	
- mass of one bale (kg)		16.8	
- maximum burn rate (bales/h)		2.68	2 bales in 45 min
- required burn rate (bales/h)		1.63	for HOTCAN design conditions
- heating value (MJ/kg)		15.24	see Appendix C
- rated input capacity (kW)		190 kW	
- rated output capacity (kW)		48 kW	based on 25% efficiency
Annual Flax Straw Requirements			
- mass (kg)		59,970 kg	based on HOTCAN results
- number of bales		3570	
- required acres of flax		132	based on 453.6 kg (1000 lb) per acre

Temperatures were monitored at the inlet and exit of each underground pipe run. The temperature drop along the pipe runs was less than 1°C, which is smaller than the experimental accuracy and indicates a trivial heat loss from the underground pipes. The insulation levels used in this project appear to be more than adequate.

The heat losses from the boiler jacket were estimated using a technique from ASHRAE (4). The outlet water temperature was controlled at 65.5°C, but the average temperature of the water jacket was somewhat lower due to temperature stratification in the tank. Heat losses from the water jacket surface were estimated to range from 1.7 kW to 3.3 kW, depending on the degree of stratification and the indoor temperature of the heating plant building. It is instructive to note that the jacket losses were sufficient to heat this building. Admittedly the building was well-insulated, but there was a considerable flow of cold air into the building to satisfy the combustion air requirements of the burner. In total, this must have constituted a considerable heat loss.

6.5 Heat Storage and Temperature Response

The system contained two large thermal storage features: the water jacket around the burner and the concrete floor slab in the workshop. The burner had to be stoked about 24 hours ahead of time to raise the temperature of the workshop by 5°C. This delay period is not unusual for slab heating systems. A forced-air heating system, using a hot-water coil, would produce a much faster air temperature response in the workshop.

The unusable heat stored in the water system was estimated to be 632 MJ. This is based on a capacity of 3870 L (850 Imp. gallons) of water in the piping and water jacket, together with a usable storage temperature of 39°C minimum. Under normal operating conditions the average water jacket temperature is 65.5°C. The average required heating for the house and workshop, based on data from Tables 4 and 5, was 871 MJ/day. Thus, for average climatic conditions, with an outdoor temperature of -12°C over the period April 1 to 7, the system is capable of storing sufficient heat for 17 hours of service. This does not account for the operation of the oil furnace during the analysed period,

and may be considerably in error.

Using the 2½% design temperature of -33.3°C (see Table 9), the heat stored in the system is capable of meeting the combined needs of the house and workshop for a period of 6 hours, based on a design heating load of 29 kW (Table 9). Of course, this time can be extended by lowering the temperature of the workshop. A decrease in workshop temperature from 16°C to 8°C would reduce the heating load to about 10kW on a day when the outside temperature fell to an average winter value of -15.5°C. This would lengthen the time to 12 hours before re-fuelling was required.

The cost-effectiveness of the flax straw heating system has been evaluated by comparing the cost of using flax straw against the cost of using fuel oil - assuming that both the house and the workshop are heated. In this comparison, the estimated annual fuel oil savings have been compared to the total costs of the flax straw system, including construction, installation and annual operating expenses.

Two methods have been used as a measure of cost-effectiveness:

- simple payback period,
- life cycle cost.

The simple payback period has been defined as the capital cost difference between the two heating systems, divided by the annual savings in fuel costs. Life cycle cost (LC) was defined by the following equation:

$$LC = \frac{\text{capital cost} + \text{life} \times (\text{fuel plus maintenance cost})}{\text{annual energy requirements} \times \text{life}} \quad 8.$$

Life refers to the lifetime of the appliance and is taken to be 20 years. Note that the above method is a 'rough-cut' approach that does not account for inflation, discount rate, escalating fuel costs or interest rate. However, it is a valid method and is often used for comparisons of this sort. Given the changeable nature of the above parameters over the last five years, a 20-year projection would be largely guesswork anyway.

A summary of the capital costs of the project is given in Table 10. The total capital cost, including materials and labour, was $18,360.67 in 1982 dollars. The baling cost, annual fuel cost and maintenance cost are summarised in Table 11, together with the costs for heating with fuel oil. The capital cost of installing a fuel-oil furnace in the workshop was estimated to be $3,000. Note that the fuel costs are based on annual heating requirements as predicted by HOTCAN (228.5 GJ).

The maintenance cost for each heating system was assumed to be 1% of capital cost.

The simple payback period, based on the costs for heating with oil, was estimated to be 6.3 years. The life-cycle cost, assuming a life of 20 years for each appliance, is:

Flax straw system - 6.68 $/GJ
Oil heating system - 13.36 $/GJ

The costs are summarised in Table 12.

Table 10. Summary of Capital Costs (1982)

Task	Description of Expenditures	Materials ($)	Subcontract ($)	Travel ($)	Total Expenditure ($)
1	Installation of underground water and electric lines	579.68	300.00	26.25	905.93
2	Erect heating plant building	4,105.06	1,587.50	152.60	5,845.16
3	Building heating unit	2,213.71	-	266.63	2,480.34
4	Install plumbing and heating in plant building	3,235.22	744.00	24.75	4,003.97
5	Install plumbing in heat distribution areas	1,110.77	115.00	71.00	1,296.77
6	Labour*				3,828.50
Total		11,244.44	2,746.50	541.23	18,360.67

* estimated by farmer

Table 11. Space Heating Cost Comparison Flax Straw Versus Fuel Oil (1982)

Cost of Heating with Flax Straw

capital cost of heating system = $18,361

number of bales required annually (HOTCAN) = 3,570

baling cost = 12¢/bale (see note below)

efficiency = 25%

annual fuel cost = $428

annual maintenance cost (1%) = $180

Cost of Heating with Fuel Oil

capital cost of oil heating system for workshop (estimate) = $3,000

fuel cost = 29.2 ¢/L

efficiency = 60%

heating value = 38.73 MJ/L

volume of heating oil required annually (HOTCAN) = 9833 L

annual cost:

- house = $1,767
- workshop = $1,105
- total $2,872

annual maintenance cost (1%) = $30

Note: The farmer paid to have the baling done, and this was the all-inclusive cost as paid by the farmer (1982 figures).

Table 12. Economics of Heating with Flax Straw Versus Fuel Oil (1982)

Simple Payback Period

capital cost difference = $15,361

annual cost saving = $2,444

payback period = 6.3 years

Life-Cycle Cost (LC) Comparison

flax-straw heating system (F)

- assumed life = 20 years
- annual energy requirement = 228.5 GJ (HOTCAN)

$$LC_F = \frac{18,361 + (20 \times 428) + (20 \times 180)}{228.5 \times 20} = 6.68 \text{ \$/GJ}$$

Oil heating system (O):

- assumed life = 20 years
- annual energy requirement = 228.5 GJ

$$LC_O = \frac{3000 + (20 \times 2872) + (20 \times 30)}{228.5 \times 20} = 13.36 \text{ \$/GJ}$$

A flax straw heating system has been designed, built and tested on a Saskatchewan farm. The system operated successfully. The monitoring results indicate that the heating system is capable of heating the farm house and workshop throughout the heating season.

The overall efficiency of the system was measured to be 25%. A two-fold increase in efficiency might be attainable by redesigning the burner to allow secondary combustion. However, this would reduce the annual fuel costs by only $214 and would give only a marginal economic improvement over the lifetime of the system. Efficiencies of 70% have been achieved elsewhere (1). This level of efficiency would not be particularly advantageous in terms of fuel consumption - which is cheap and plentiful. But it would be advantageous from an operational point of view. Higher efficiencies mean longer times between refuelling. This would improve the operational convenience of the unit and would probably make it impracticable to talk about automatic fuelling systems.

Automatic fuelling systems are available in commercial designs for flax straw burners. These cut up the bales and feed them into the burner using an auger system. The flax straw burner used in this project could be modified to accept an automatic feed, but this would add to the capital cost. Automatic feed is therefore a matter of trading-off capital costs against convenience. In the long term, assuming that this prototype burner is developed into a production unit, an improved efficiency would make automatic feed a matter of less concern.

A comparative summary of fuel costs is shown in Table 13. Note that the 12¢-per-bale cost for flax straw has been escalated by 5% per year to arrive at the 1984 figure of 13.2¢/bale. The fuel cost per unit of heat output is twice as good for flax straw as for its nearest competitor - natural gas. It is a factor of 5 better than the other alternatives - wood, oil or electricity.

The economic evaluation has taken into account all the main cost items and has shown that, on the basis of life cycle costs, a flax straw heating system is a factor of 2 better than an oil heating system of

similar capabilities ($6.68/GJ as opposed to $13.36/GJ). The simple payback period was calculated to be 6.3 years for the flax straw heating system.

The calorific value of a bale of flax straw was measured to be 75% higher than that of a U.S. gallon of fuel oil. Given efficiencies of 25% for flax straw combustion and 60% for fuel oil combustion, the heating output of the flax straw is approximately 27% lower than that of fuel oil. This finding, however, is specific to the design of burner used in this project. The above comments indicate that considerably higher efficiencies can be achieved, and this would bring flax straw more on a par with fuel oil.

There were hardly any operating problems with the flax straw heating system. No water leaks were encountered and the risk of freezing can easily be avoided by increasing the glycol content in the water to 50%. Although the thermal response of the system was slow, the heat stored in the system is capable of meeting the combined heating load of the house and workshops through most winter nights, without the need for re-fuelling. An improvement in combustion efficiency would be beneficial in this regard.

An important problem with the existing system design is the low flue gas temperature. This results in condensates, including creosote, running down the chimney. In turn, this could create chimney fires if the problem is not attended to. The low flue gas temperature also causes a poor natural draft in the chimney. Both problems can be minimised by incorporating secondary combustion processes in the burner design.

It should be noted that straw burners of this type can be modified for grain drying, and can use other kinds of fuel, such as crop residues or wood.

Table 13. Fuel Cost Comparison (1984)

Type	Cost/Unit	Efficiency (%)	Fuel Cost/Unit Output ($/GJ)
Flax Straw	13.2 ¢/bale [4]	25	2.06
Wood [1]	100 $/cord	50	9.76
Natural Gas [2]	13.81 ¢/m^3 [3]	65	5.70
Fuel Oil	30.7 ¢/L	60	13.21
Electricity [3]	4.02 ¢/kWh	100	11.17

1 - 2500 lb/cord , 7770 Btu/lb

2 - includes $9.25/month service charge and 5% E and H tax

3 - includes $6.00/month service charge and 5% E and H tax

4 - A 10% increase has been applied to the 1982 figure given in Table 11. The cost is realistic for the operations of this particular farm, and has therefore been used as the basis for cost analysis. However, according to information supplied by Mr. B. Zuk of SRC, some farmers may pay as much as 55¢ to 74¢ per bale (1984 figures).

A home-made flax straw burner has been designed, built and operated. The system was designed to meet the space heating needs of a farm house and a workshop. Heat was delivered from the burner to these two buildings by a hot water system, fed from a water jackets around the burner. The workshop was heated by hot water pipes embedded in the concrete floor slab; the house was heated by an A-coil hot water unit mounted in the plenum of the existing oil furnace unit.

The system was monitored over a period of about six weeks. For a large proportion of this time the monitoring records were disrupted by power line problems, and the analysis of the system has therefore been based on seven days of trouble-free operation in April 1982.

The system operated satisfactorily when electrical power was available. There were no leaks and no signs of freezing. The absence of freezing problems is partly a reflection on the design and partly fortuitous. Had the system been out of service for a day or more, it is likely that freezing problems would have occurred in the buried supply lines. The water system had a 10% glycol concentration. By increasing this to around 50% it would be possible to eliminate freezing problems, but at the same time this would add to the cost of the system.

The measured efficiency of the system was 25%. This low value is due mainly to incomplete combustion and jacket losses - although the latter serve a useful function in keeping the heating plant building warm. Heat losses from the buried water lines were found to be trivial.

Since the flax straw is cheap and readily available, the combustion efficiency is not an important factor from the point of view of fuel usage. However, it has an important effect on the convenience of operation. Flax straw burners are commercially available with efficiencies up to 70%. If the efficiency of the tested system had been around this level, then the unit would have required re-charging less frequently. With a high-efficiency unit the task of

re-charging is not inconvenient, but if the efficiency is as low as 25% - as in this case - the re-charging becomes inconvenient to the point where an automatic feed would be advisable. Taking the design as it stands, it could be improved either by incorporating a secondary combustion system to increase the efficiency, or by maintaining the existing level of efficiency and adding an automatic feed. Both options add to the capital cost of the system, and one trades off against the other.

The cost of the system, including materials and labour, was about $18,360. Salvage material was used in the construction, and therefore this cost cannot be regarded as accurate for general use. Future units of a similar design could be expected to show the same order of capital cost.

The system was monitored towards the end of the heating season, during which time the buildings were not exposed to anything approaching worst-case winter conditions. With the help of the HOTCAN computer program it has been estimated that the flax straw system is capable of heating both the house and the workshop on the coldest days in winter - and with a comfortable margin of heating capacity.

On average, the flax straw system will require about 3,570 flax straw bales per heating season. This can be got from about 132 acres of flax crop, based on an estimated yield of 453.6 kg of flax straw per acre.

The economics of the flax straw system are encouraging when assessed against the use of fuel oil. The simple payback period was estimated to be 6.3 years. The life-cycle cost, based on an assumed 20-year life, was found to be about twice as good as that of a comparable fuel-oil heating system:

Flax straw system	6.68 $/GJ
Oil heating system	13.36 $/GJ

Note, however, that in this particular project the cost of baling the flax straw appears to have been atypically low.

In total, the flax straw heating system appears to be a good alternative for those farmers who have access to flax straw and are considering an off-oil conversion. The system is relatively trouble-free and the economics are favourable. The only drawback is the low efficiency of the unit (25%). While this is tolerable in terms of fuel consumption, it does involve a lot of unnecessary re-charging, which can become inconvenient. In future designs it would be advisable to increase the system efficiency by incorporating a secondary combustion system.

1. Arno Strehler. "Energy from Straw - A Comparison of Some Straw-Burning Furnaces." Agricultural Wastes 0141-4607/80/0002-0241. Applied Science Publishers Ltd. England 1980.

2. Dumont, R.S., Lux,M.E. and Orr, H.W."HOTCAN: A Computer Program for Estimating the Space Heating Requirements of Residences." Computer Program No. 49, NRC, Division of Building Research, 1982.

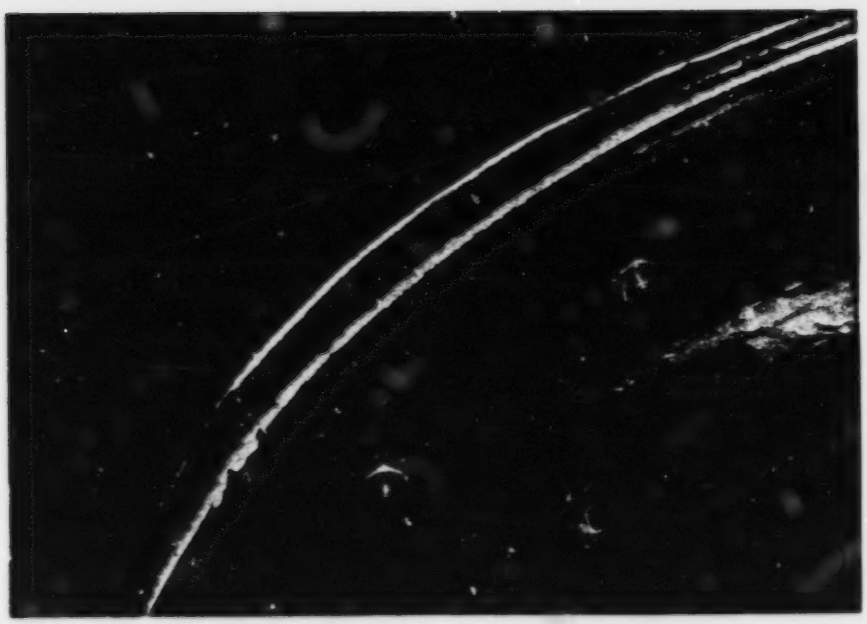
3. R.M. Graham, "Residential Oil Furnace Seasonal Efficiency." CEA Project 911 U 137, SPC R&D Centre, 1981.

4. ASHRAE Handbook of Fundamentals, 1981 Published by ASHRAE, Atlanta, GA. 30329

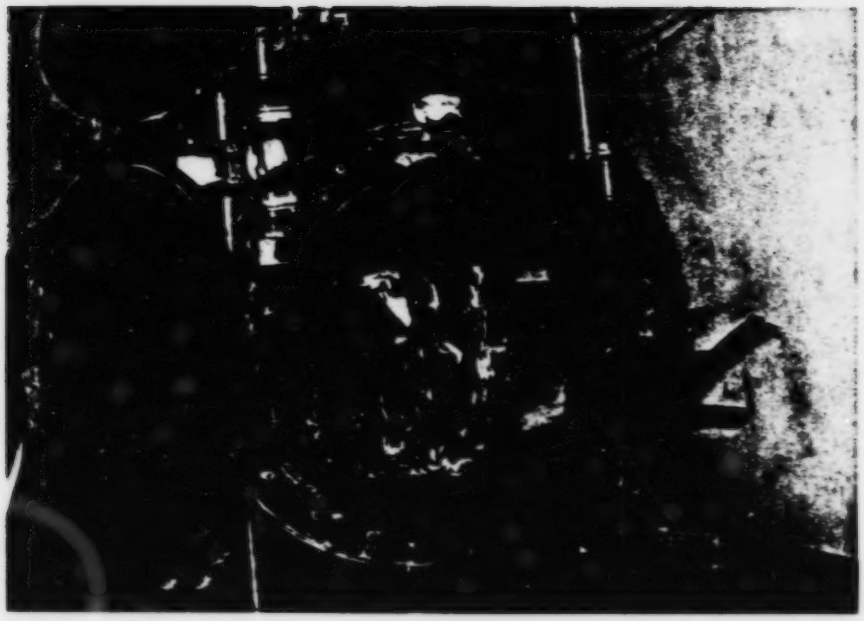
APPENDIX A

Photographs of Construction and Installation

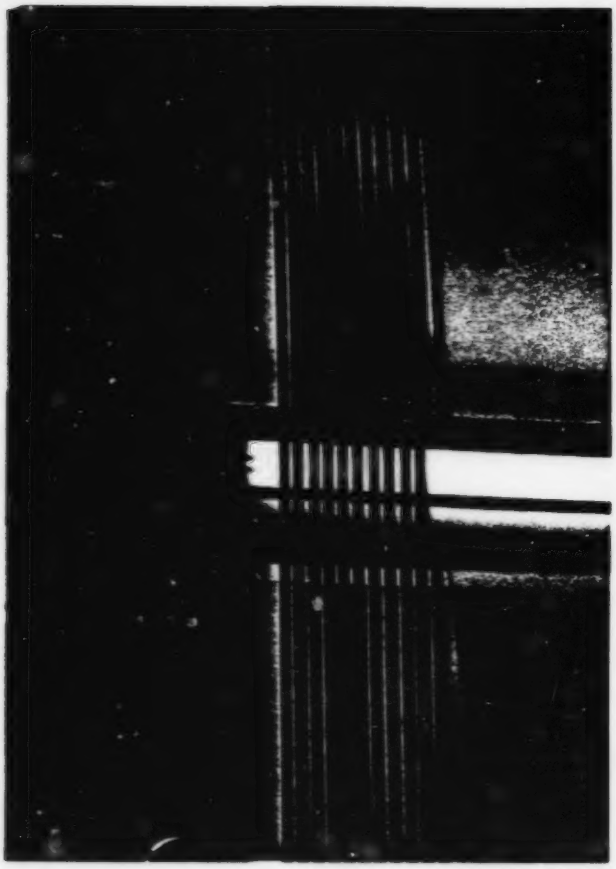
Prototype Flax-Straw Burner



Neoprene Gasket Assembly

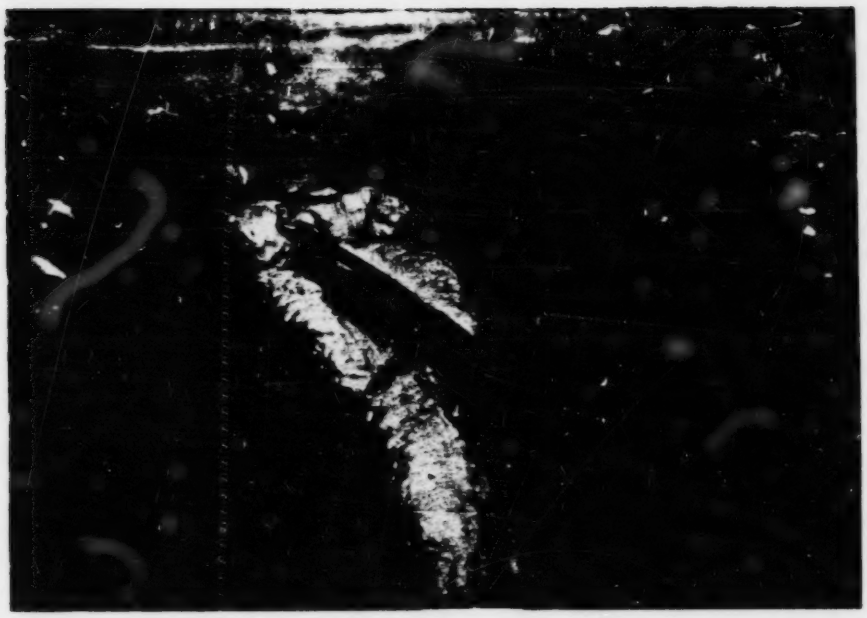


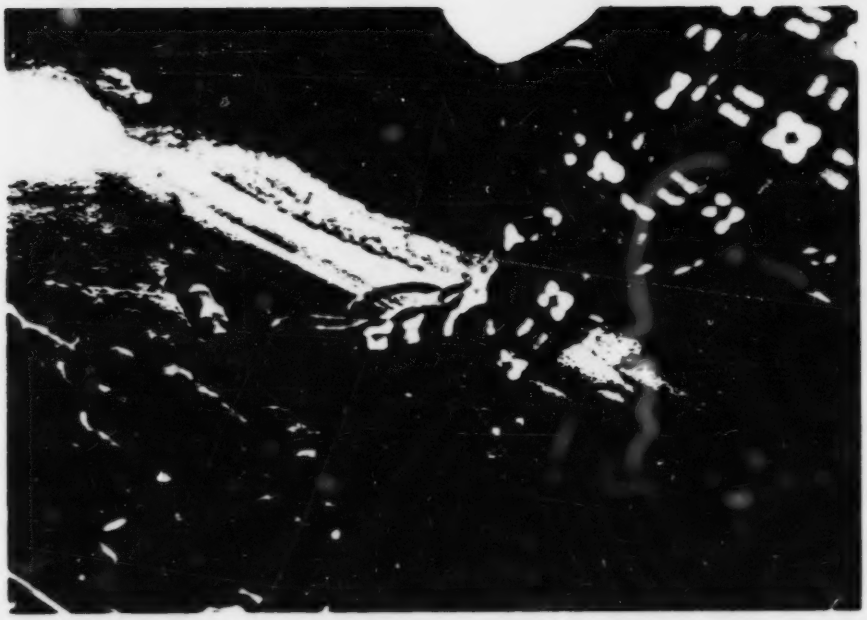
Flax-Straw Burner



Heat Exchanger Piping

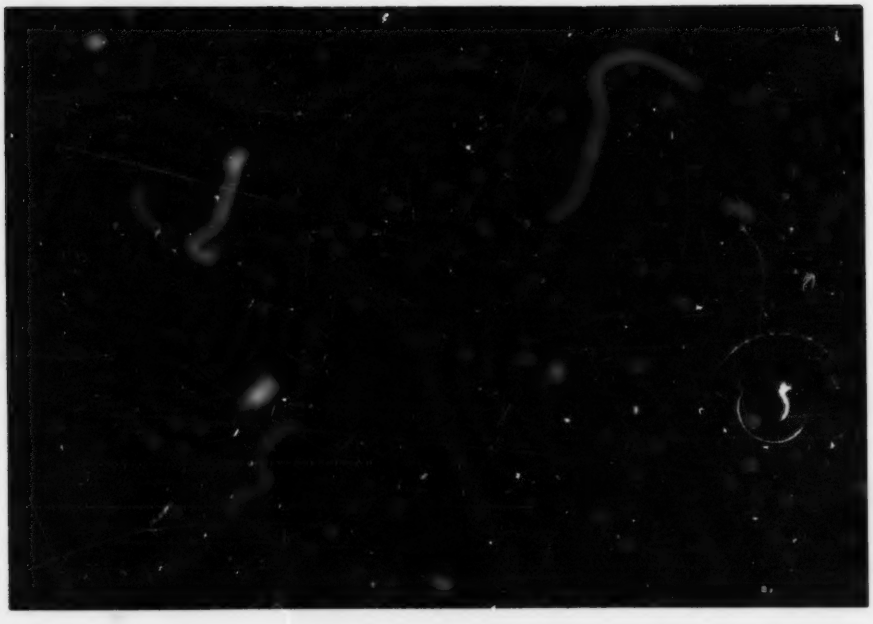
Thermocouple Wiring, Electrical
Wiring and Underground Piping

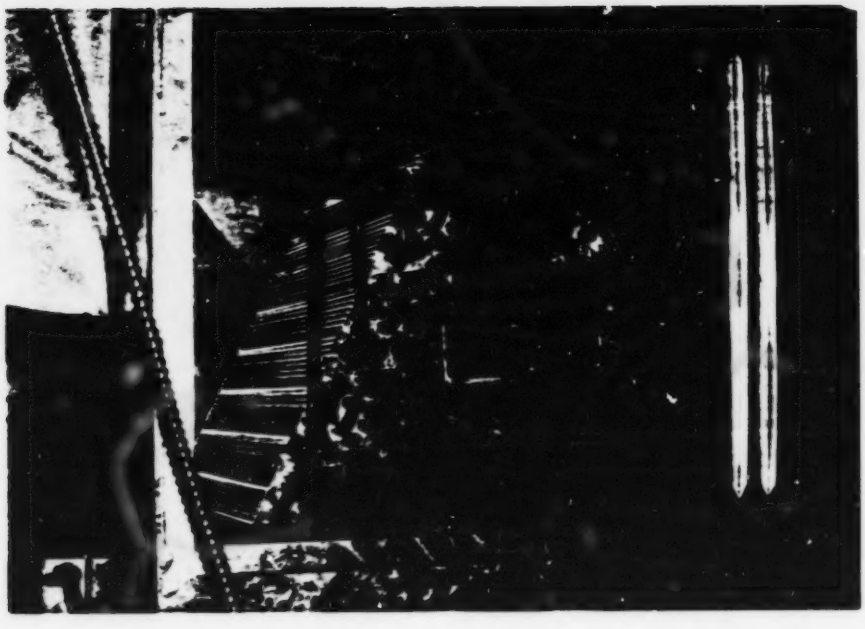




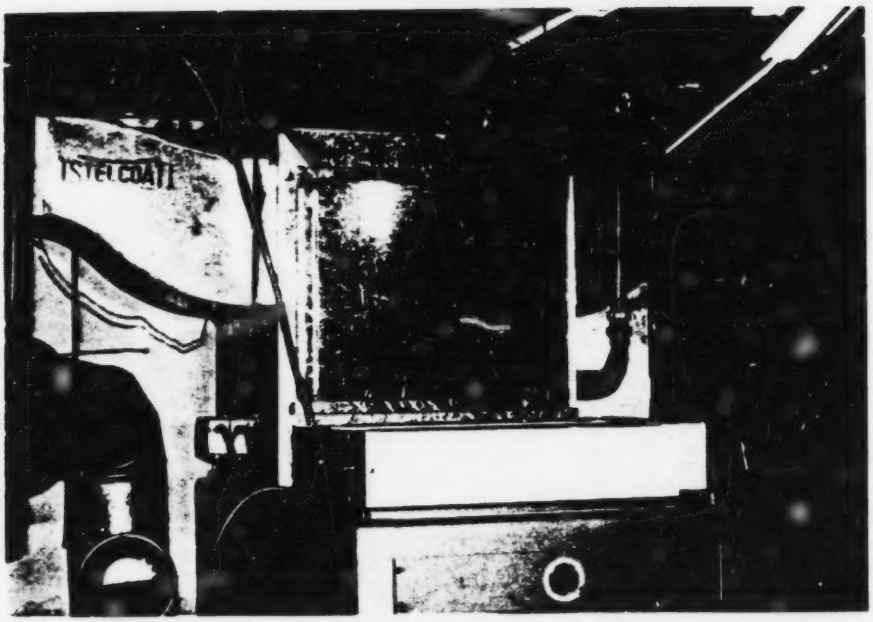
Insulating Underground Piping

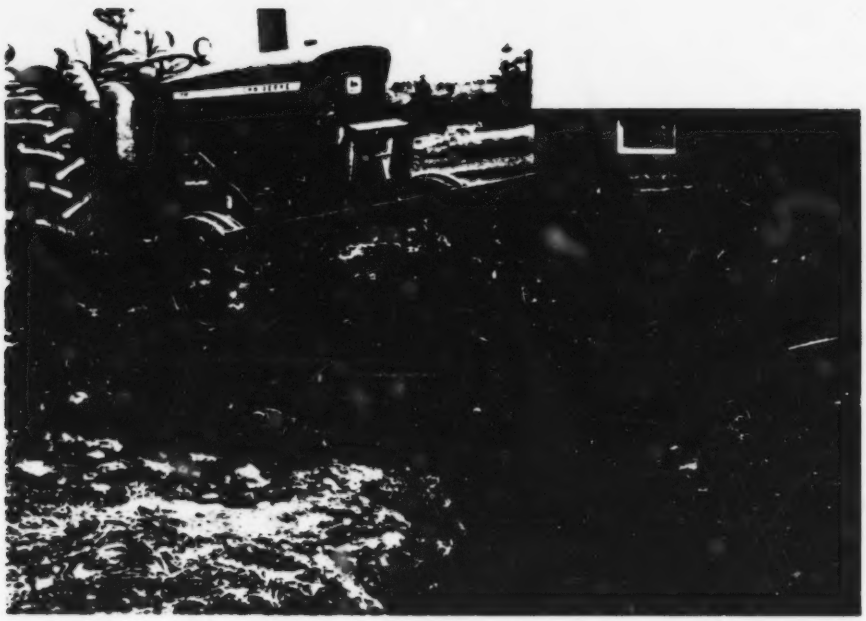
Piping to Workshop



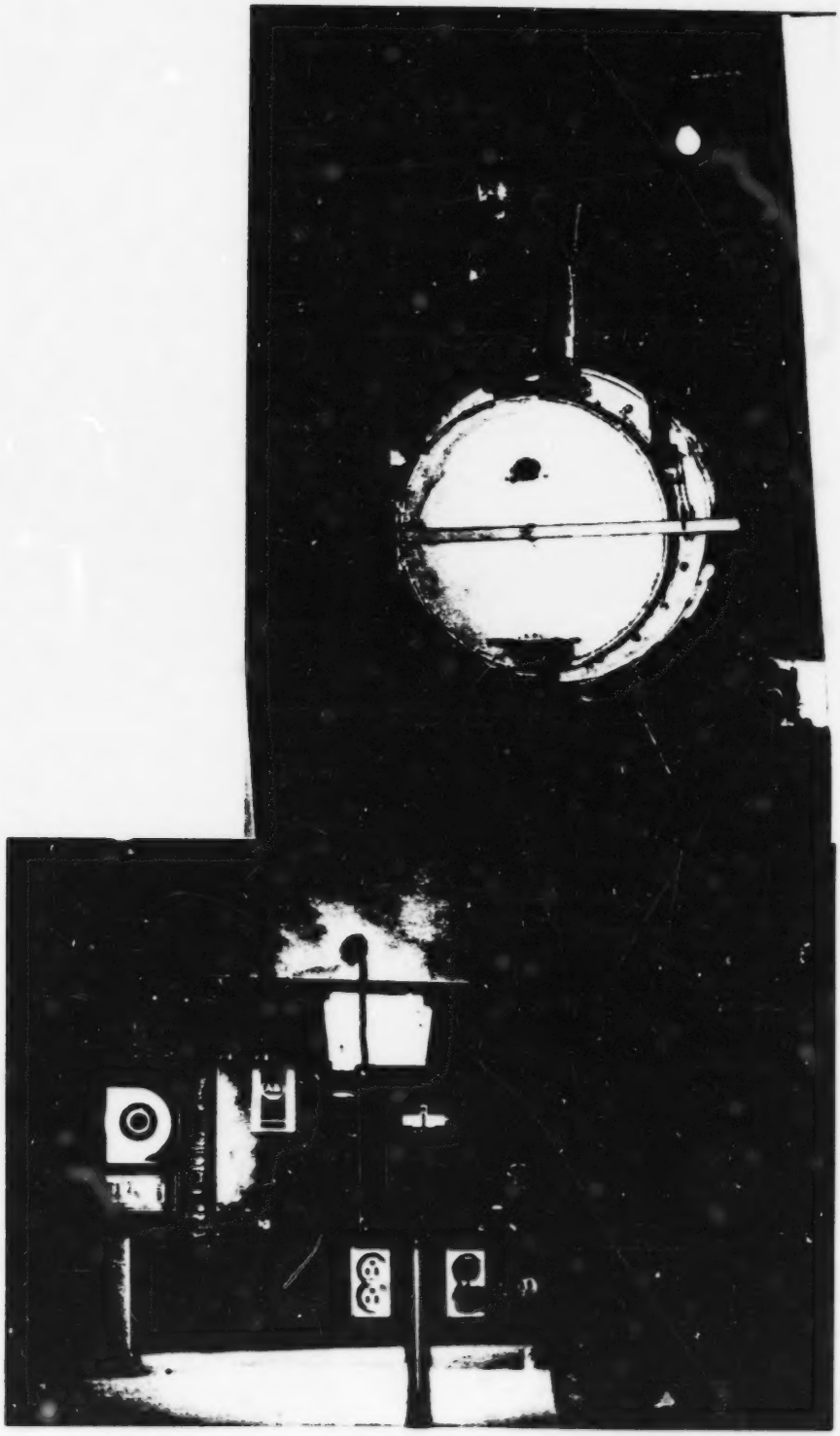


House Heating System: Thermostats and A-Coil





Furnace Assembly and Piping to House



Flax-Straw Burner and Controls in Heating Plant Building

Details, Specifications and Geometry of the Heating System

DETAILS AND SPECIFICATIONS FOR THE HEATING SYSTEM (provided by the farmer)

Flax-Straw Burner:

- the boiler was a 1000 gallon underground tank.
- the fire-box was a 26" diameter x 12' length x ¼" thick steel pipe.
- the chimney was 14" x 8" class A type.
- the ring gasket seal was 1/8" thick Garlock (neoprene material).
- the pumps were Bell & Gosset model S.100 bronze circulation pump and Grundfos model 40-75 U hot water circulation pump (latter preferred).
- inside of the water jacket and exterior of the firebox were painted with a green epoxy paint.
- thermometers were Ametech gauge model T-571.
- the chimney induced draft fan was Tjernlund Inline Auto Draft Inducer.
- approximately 135 gallons of antifreeze was used in the heating system.
- rust inhibitor used was about ½ gallon.
- total liquid capacity of the entire heating system was 850 gallons.
- underground pipes were 1.0" diameter, 75 psi black polyethylene pipe.

Trench and Pipes:

- trench dimensions were approximately 4' deep and 1½' wide.
- the distance between heating plant building and workshop is about 70'.
- the distance between heating plant building and house is about 120'.
- water pipes were 1" diameter and 75 psi black polyethylene.
- insulation was spray-on type supplied by K-P Insulating of Rosetown; minimum cover of R20 with most received approximately R30.
- electrical power for the heating plant building was supplied from the workshop by underground 3 conductor cable.

DETAILS AND SPECIFICATIONS FOR THE BUILDINGS (provided by the farmer)

House Area:

- the 'A'-coil mounted in hot air plenum immediately above the existing furnace was rated for 36000 BTUh cooling and 90000 BTUh heating.
- all water lines in the house was 1" diameter copper tubing.
- walls were constructed of 2x4 studs with R12 insulation; ceiling with R32 insulation.

Shop Area:

- walls were constructed of 2x6 studs with R20 insulation and 5/8" drywall.
- slab heat was supplied by 1200' of 1" diameter polyethylene pipe in 4 circuits.
- manifold for distributing incoming hot water into 4 circuits was made from 2"x2"x3/16" square tubing and valves.
- a total floor area of 3000 ft^2 and volume of 36000 ft^3.

Heating Plant Building

- 2x6 walls with R20 insulation; ceiling with R20 insulation.
- metal roof was Revelstoke Weathertite.
- dimenstions were 14'x24' (336 ft^2) and volume of 2688 ft^3.
- exterior door was wood type and inside partition door was steel type.

Proximate Analysis of Flax-Straw

MAJOR CONSTITUENTS		
C, total	%	43.5
H	%	5.7
Oxygen, calc.	%	47.7
S, dry	%	0.14
NUTRIENTS		
N	%	0.2
PHYSICAL PROPERTIES		
Ash, dry	%	2.8
BTU value, dry	BTU/lb	8114
Moisture	%	7.1

PROXIMATE ANALYSIS OF FLAX-STRAW

Heating Value of Flax-Straw

Heating value of flax-straw by proximate analysis = 8114 BTU/lb (dry).

Assumed moisture content = 20% (included snow and moisture accumulation in bale).

Dry weight in one pound of flax-straw : $1 \times \frac{1}{1+20\%}$ lb.

= 0.833 lb.

The low heating value of flax-straw (@ 20% m.c.):

(8114 x 0.833) - 970 x (1 - 0.833) - 200 x (1 - 0.833)

= 6564 BTU/lb. (15.24 MJ/kg)

The heating value is adjusted to account for the sensible and latent heat of the water in the flax-straw.